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# Reconstructing Palaeogeography and Inter-island Visibility in the Wallacean Archipelago During the Likely Period of Sahul Colonization, 65–45 000 Years Ago

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ABSTRACT The palaeogeography of the Wallacea Archipelago is a significant factor in understanding early modern human colonization of Sahul (Australia and New Guinea), and models of colonization patterns, as well as archaeological survey and site interpretation, are all heavily dependent on the specific palaeogeographic reconstruction employed. Here we present five reconstructions for the periods 65, 60, 55, 50, and 45 000 years ago, using the latest bathometric chart and a sea-level model that is adjusted to account for the average uplift rate known from Wallacea. Using this data we also reconstructed island areal extent as well as topography for each time period. These reconstructions were then used to estimate visibility for each island in the archipelago, and finally to model how intervisible each island was during the period of likely human colonization. Our models provide the first evidence for intervisibility between Timor and Australia at ca. 65–62 ka and 47–12 ka, the second of which is notable for its overlap with the oldest radiocarbon dates from Timor-Leste and Australia. Based on intervisibility alone, however, our study suggests that the northern route into Papua New Guinea was the most parsimonious route for first modern human entry into Sahul. Our study provides archaeologists with an important baseline from which to conduct physical surveys, interpret archaeological data, and theorize the colonization of Wallacea and Sahul. © 2017 The Authors. *Archaeological Prospection* Published by John Wiley & Sons Ltd.

*Key words:* Wallacea; intervisible; Sahul; Sunda; migration; palaeogeography

## Introduction

Palaeogeography concerns the study and reconstruction of the Earth's continents and oceans throughout its geological past. Understanding the palaeogeography of a particular region is vital for interpreting the ecology, distribution, diversity, and evolution of organisms in those regions (Benton and Harper, 2009). The biogeographic region of Wallacea, defined as the archipelago lying between the continental shelves of southeast Asia (Sunda) and Australia-New Guinea (Sahul) to the exclusion of the Philippines (and thus following the extent of Wallace's original line; see Kealy *et al.*, 2015), is a key archaeological prospection zone. An understanding of the palaeogeography of Wallacea significantly impacts our interpretations of the region's archaeology, and is vital for reconstructing movements of anatomical modern humans (AMHs) through the region and their first arrival on Sahul (Birdsell, 1977; Butlin, 1993; Kealy *et al.*, 2015). Four possible routes of dispersal from Sunda to Sahul have been suggested (Birdsell, 1977; Sondaar, 1989; Morwood and Van Oosterzee, 2007), largely reflecting Birdsell's (1977) 'northern' (New Guinean) or 'southern' (Australian) routes (Birdsell, 1977; Kealy *et al.*, 2015; Figure 1). While Birdsell (1977) favoured the northern route (Route 1) based on intervisibility between these island chains, O'Connor *et al.* (2010) suggested that current archaeological evidence from Wallacea could be used to support either possibility, though with the oldest dates for AMH occupation recovered from sites in Timor-Leste favoured the southern route (O'Connor, 2007; Figure 1).

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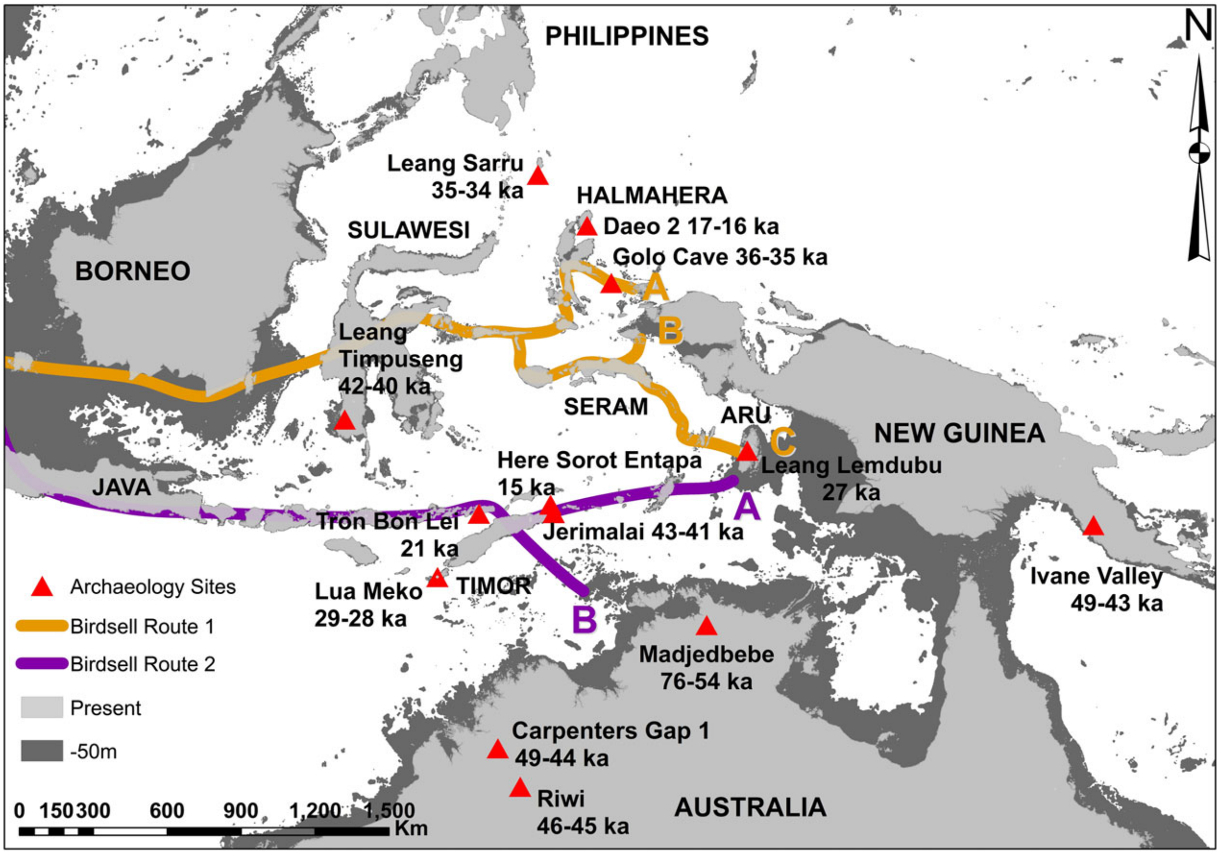


Figure 1. Map of Wallacea and neighbours showing Birdsell's (1977) potential Sahul colonization routes, and the various archaeological sites mentioned in the text. Calibrated date ranges are included in brackets, rounded to 1 ka. The extent of the continental shelf down to the −50 m bathometric contour is shaded in dark grey. [Colour figure can be viewed at wileyonlinelibrary.com]

Hypotheses of migration made on the basis of molecular data have also been used to infer the direction, pattern, and timings of Sahul colonization (e.g. Redd and Stoneking, 1999; Oppenheimer, 2003; van Holst Pellekaan, 2013). Unfortunately, they have added little clarification to the different possibilities suggested by the archaeological data. In part this is the result of the use of archaeological data to calibrate molecular models, creating circularity between the results of the two approaches (Allen and O'Connell, 2014). This issue notwithstanding, most molecular models are examined at a broad geographical scale that obscures regional patterns, because the focus of such models is on Out-of-Africa and global colonization rather than how AMHs made it into Sahul (e.g. Underhill *et al.*, 2001; Oppenheimer, 2003, 2009, 2012; Endicott *et al.* 2007). Thus, genetic sampling in Wallacea and Sahul is comparatively limited in relation to other sampled populations in these studies (e.g. Redd and Stoneking, 1999; Fregel *et al.*, 2015). Despite these limitations, global models do provide useful information concerning the timing and rate of Sahul colonization, with most studies suggesting an initial arrival date of about 50 ka, and a period of ca. 5 to 30 ka for complete dispersal between Asia and Sahul (Hill *et al.*, 2007; Hudjashov *et al.*, 2007; McEvoy *et al.*, 2010; Oppenheimer, 2012; van Holst Pellekaan, 2013; Fregel, 2015; Bergström *et al.*, 2016).

It should be noted that not all molecular studies are based on unevenly sampled populations, and some are quite data-rich for Wallacea and Sahul; however these tend to focus on more recent migration patterns (e.g. Redd *et al.*, 2002; Soares *et al.*, 2008; Jinam *et al.*, 2012; Tumonggor *et al.*, 2013). A case in point is the mitochondrial study by Hill *et al.* (2007), where about 20% of the modern inhabitants sampled in Island South East Asia (ISEA) had mtDNA haplotypes that can be traced to the first AMH to colonize the region. The other 80% of inhabitants trace their origins back to more recent Holocene migrations out of Indochina, Taiwan, and Near Oceania, and these provide the majority of genetic data for ISEA (Hill *et al.*, 2007). A more recent analysis by Gomes *et al.* (2015) focused on the AMH migration from Sunda to Sahul, and



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compiled over 16 thousand samples from 33 different geographic locations. Their analysis suggested that both the northern and southern routes were used in the colonization of Sahul, thus supporting other molecular models (Ingman and Gyllensten, 2003; Oppenheimer, 2009; McEvoy *et al.*, 2010; Rasmussen *et al.*, 2011; van Holst Pellekaan, 2013).

While excavations on the islands along the different proposed routes are ongoing, archaeologists have yet to recover evidence of AMH occupation that pre-dates the colonization dates from Sahul, and thus provide support for any particular route. Understanding the route of AMH dispersal through Wallacea is not just an academic pursuit. It can assist with interpretations of early marine technologies and consequently aspects of tool development, communication and social/community structures (Bednarik *et al.*, 1999; Balme, 2013). With over 2000 islands in Wallacea, understanding the most likely route(s) taken by AMHs is also advantageous when selecting particular islands for archaeological attention. Additionally, the choice of 'landing site' for Sahul colonization has wide ranging impacts on all models of subsequent colonization of Greater Australia, and Island Melanesia (Birdsell, 1977; Irwin *et al.*, 1990; Clark, 1991; Field and Lahr, 2005; Clark *et al.*, 2008). Until more illuminating archaeological evidence is found, computer simulations and mathematical models can be used to predict likely patterns of AMH movement, and in turn, these models can inform subsequent archaeological survey efforts (Kealy *et al.*, 2015). A key variable in such models is palaeogeography (Van Andel, 1989; Oppenheimer, 2009; O'Connell *et al.*, 2010). In Wallacea in particular, the method and extent of palaeogeographic reconstruction plays a significant role in dispersal model outcomes (Kealy *et al.*, 2015), and a detailed reconstruction of palaeogeography is vital for testing the validity of the various proposed models of AMH dispersal to Sahul.

## Materials and methods

The Wallacean archipelago is a zone of incredibly high tectonic activity and geological complexity that results from the simultaneous collision of three tectonic plates (Eurasian, Indian-Australian and Pacific-Philippine Sea; Hall, 2009). Consequently, Wallacea has experienced a significant degree of tectonic uplift since the time of initial AMH colonization. Birdsell (1977) used the palaeoclimatic model of Chappell (1976) to lower sea-levels by 150 m (to account for Pleistocene glacial conditions), then added 150 m to present island heights to account for the lowered sea-levels (as elevation is measured in metres above sea-level). Birdsell (1977) then used these reconstructed island heights, widths, and the distances between islands to infer inter-island visibility and ease of prehistoric travel. His model, however, neglected to account for the region's extensive tectonic uplift (Birdsell, 1977). Our palaeogeographic reconstructions of Wallacea essentially represent an updated, quantitative, and digitized analysis of Birdsell's (1977) island intervisibility hypotheses with the important addition of an uplift variable.

The study of island uplift in Wallacea is not comprehensive, rather, select studies on only specific islands has left much of the differential uplift rates in the region in question. Thus, in order to account for uplift in our palaeogeographic reconstructions, we calculated the average uplift rate for Wallacea from different rates recorded for islands in the region (Table 1). While the use of an average will result in slight over- and under-estimates of uplift for some islands, until more data is available, the average rate provides a reasonable approximation for this variable. We then used this average uplift rate to reconstruct an adjusted sea-level curve for Wallacea (Figure 2) based on the palaeoclimactic model of Lambeck and Chappell (2001). Because most studies posit colonization of Sahul occurred sometime around 45–65 ka (Hill *et al.*, 2007; Hudjashov *et al.*, 2007; Oppenheimer, 2012; van Holst Pellekaan, 2013; Bergström *et al.*, 2016), we produced reconstructions for five periods spanning this interval: 65 ka, 60 ka, 55 ka, 50 ka, and 45 ka. The resultant difference between ancient and current sea-levels for each of the five time periods were then applied to the most recent bathymetric chart of Wallacea, obtained from the General Bathymetric Chart of the Oceans (GEBCO_14) dataset (Smith and Sandwell, 1997 and downloaded from http://www.gebco.net/), using ArcGIS [Environmental Systems Research Institute (ESRI), 2014].

We calculated the distance to the geometric horizon according the formula $d = \sqrt{2}r$, where $d$ is the distance to the horizon, and $r$ is the radius of the Earth. Ignoring refraction, this resulted in a distance of 3.57 km to the geometric horizon. We incorporated two different heights extending above the Earth's surface (equivalent to a person's eye height and the top of a mountain) using the following formula:

$$\text{Visibility (km)} = \left(3.57\times\sqrt{h_1}\right) + \left(3.57\times\sqrt{h_2}\right)$$

where $h_1$ is the eye height of the viewer (in metres) and $h_2$ is the height of the island (in metres).



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Table 1. Uplift rates calculated for different islands throughout Wallacea. Modified from Pedoja *et al.* (2014, table 1).

| Island/region | Site location | Proposed maximum record | Apparent uplift rates (m/ka) | Dating method | Reference |
|---|---|---|---|---|---|
| East Timor | Atauro | Plio-Quaternary | 0.516 | U/Th | Chappell & Veeh, 1978 |
| East Timor | Baucau/Ponta Bondura | Not known | 0.553 | U/Th | Cox, 2009; Chappell & Veeh, 1978 |
| East Timor | Hau | Not known | 0.082 | U/Th | Chappell & Veeh, 1978 |
| East Timor | Lautem | Not known | 0.41 | U/Th | Chappell & Veeh, 1978 |
| East Timor | Laga | MIS 7 | 0.5 | U/Th | Cox, 2009 |
| West Timor | Namosain | MIS 7 | 0.3 | U/Th | Jouannic *et al.*, 1988 |
| West Timor / Semau Island | Cape Oeloimi | >MIS 5e | 0.328 | U/Th | Jouannic *et al.*, 1988 |
| Rote Island | Point Dombo | >MIS 5e | 1.4 | U/Th | Roosmawati & Harris, 2009 |
| Savu Island | West Savu | >MIS 5e | 0.7 | ESR/U/Th | Roosmawati & Harris, 2009 |
| Sumba Island | Cape Laundi | 1 Ma | 0.49 | ESR | Nexer *et al.*, 2015; Pirazzoli *et al.*, 1993 |
| Alor Island | Kabola | > MIS 15 | 1.2 | $^{14}$C/U/Th/ESR | Hantoro *et al.*, 1994 |
| Kisar Island | Kisar | MIS 9 | 0.5 | U/Th | Major *et al.*, 2013 |
| East Sulawesi | Luwuk | MIS 7 or older | 0.18 | U/Th/$^{14}$C | Sumosusastro *et al.*, 1989 |
| East Sulawesi | Luwuk | MIS 9 or older | 0.336 | U/Th/$^{14}$C | Sumosusastro *et al.*, 1989 |

The equation thus takes into account the increasing visibility that results as the object being viewed (the island) extends upwards from the Earth's surface ($h_2$) in addition to the degree to which visibility is increased as a result of eye height above sea level ($h_1$). Further corrections to account for atmospheric refraction (which increases the visibility distance) are possible; however as the equation also operates under the assumption of perfect weather conditions we chose to use the simpler equation and avoid over-estimation of visibility. Furthermore, we elected to use a height of only 0.5 m for the viewer's eye height. Again, this under-estimates visibility for most individuals viewing from the shore; however, it allows us to accommodate the likelihood that the viewer is not standing but rather seated in some type of craft such as a raft or canoe (Friedman *et al.*, 2010). For example Alor Island has an estimated elevation of 1717 m at 45 ka. Thus a person whose eye is approximately 0.5 m above sea level would have been able to see Alor up to 150 km away. If that person was to stand up, however, and their eye was then 1.8 m above sea-level, they could see the island up to 152.7 km away.

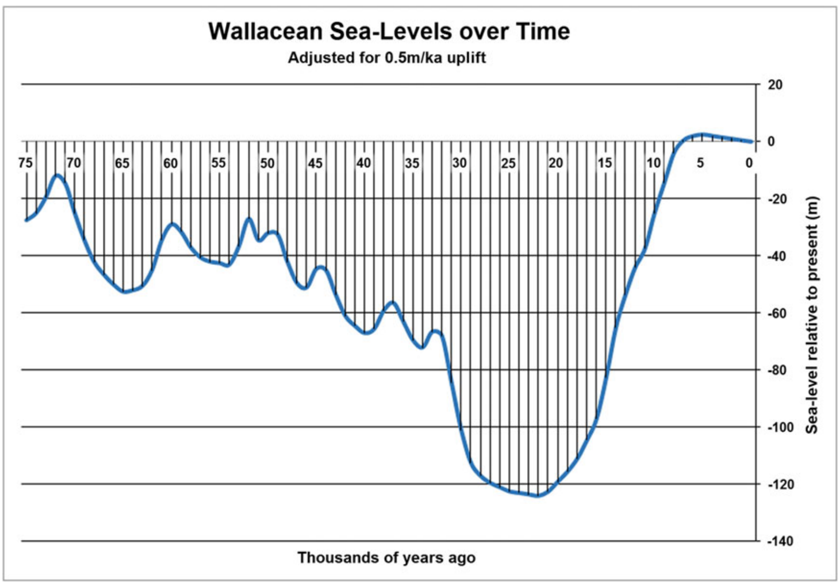


Figure 2. Sea-level curve adjusted for an average uplift rate of 0.5 m/ka for Wallacea for the last 75 000 years. Sea-level data from Lambeck and Chappell (2001), uplift rate calculated from Table 1. [Colour figure can be viewed at wileyonlinelibrary.com]



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After calculating the visibility for each island according to their reconstructed heights at the five different time periods, we calculated the distances out to sea that the individual island could be seen using the 'buffer' tool in ArcGIS and our reconstructed island coastlines. Areas where this 'buffer zone' overlapped were thus areas of continuous island-to-island visibility. In other-words, overlap indicated that one could travel by canoe (or some other type of water craft) between two islands without ever going out of sight of land. This is not an indicator that one island can be seen from the shore of another (see later), but that whilst travelling, before someone is completely out of sight of the starting island they are in sight of the next. We term this 'relative intervisibility', as two islands are visible from a point at sea between their shores, relative to the observer.

Absolute intervisibility is used to define islands that are visible from the shore of another. The calculation of a wholescale, shore-to-shore visibility model (absolute intervisibility) is exponentially more computationally intensive than the relative intervisibility model: rather than determining the distance at which an island can be seen, absolute intervisibility requires knowledge of which of all the surrounding islands can be spotted from the shores of each other. As the islands are of significantly varying heights, a precise analysis of absolute intervisibility requires multiple and simultaneous island directional analyses. While such analyses would no doubt provide precise indications of visibility relationships between islands, this degree of detail was deemed unnecessary for our study.

Rather, we proceeded with the (computationally simpler) assumption that islands were of the same approximate height, such that halving the islands' relative intervisibility produced an area of overlap indicating approximate absolute intervisibilty. This is because if the relative intervisibility buffer of one island, which highlights all areas from which that island can be seen, touches the coast of a neighbouring island, then that indicates that the first island can be seen from the shores of its neighbour (absolute intervisibility). Halving the visibility distance of two absolutely intervisible islands of the same height results in each 'half buffer' merging to form an absolute intervisible buffer equal to the islands' relative intervisibility buffer – in other words indicating that each island falls within the other's zone of visibility. This method allows for the study of the archipelago as a whole by displaying chains of continued (approximate) absolute intervisibility everywhere these 'half buffers' overlap. While this approach introduces a 'highland bias,' as the analysis is not directional and can thus cause low islands to look as though they are visible from the shore of a higher island (when in fact it is only the higher island that is visible from the shores of the lower one), a higher island also offers the viewer with a higher lookout point should they climb inland, thus effectively mitigating this bias. Furthermore, we consider absolute intervisibility to be less relevant to migrating people than relative intervisibility. If AMHs in Wallacea had the marine technology and skill to travel notable distances from their 'home' shore in pursuit of marine resources (O'Connor *et al.*, 2011; Samper Carro *et al.*, 2016), then the likelihood is that new islands were initially spotted at sea rather than from land. Therefore, we argue that relative intervisibility provides a better indication of how the Wallacean archipelago might have been viewed by Pleistocene peoples.

In addition to interpretations of intervisibility, we used our palaeogeographic reconstructions to investigate the locations of the oldest sites known from islands with Pleistocene occupation dates. We compiled a dataset, calculating the distance from the coast and elevation of the archaeological sites at their oldest known occupation, as well as the size of the island at that time (Table 2). Using a non-parametric rank correlation analysis (Spearman's rho), we tested whether any correlation between any of our geographic measurements and the timing of first occupation existed.

## Results

We produced five separate maps representing the palaeogeography present at 65 ka (Figure 3), 60 ka (Figure 4), 55 ka (Figure 5), 50 ka (Figure 6), and 45 ka (Figure 7). Each of these maps shows the reconstructed coastlines, island topography, relative intervisibility and approximate absolute intervisibility for these time periods. Our results show the greatest visibility for the periods of 65 and 45 ka, with the least visibility occurring at 60 ka. The northern islands between Sunda and Sahul show continued relative intervisibility between 65 to 45 ka, while visibility is less continuous towards the south. Relative intervisibility between Timor and Australia is present at 65 and 45 ka through a small emergent island chain to the north of Darwin and the Tiwi Islands, but absent in the other reconstructions. Interpolating from the five maps in light of the uplift-adjusted sea-level curve (Figure 2), this Timor-Australia relative intervisibility was also likely present between 65 and 62 ka and 47–12 ka. According to estimates for absolute intervisibility, at no time



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Table 2. Archaeological sites with the oldest known occupation dates (maximum calibrated age BP, 95.4% probability range) for Wallacean islands with Pleistocene data.

| Island | Site | Date of initial occupation (maximum ka) | Reference | Distance to coast (km) | Elevation (km) | Island size ($km^2$) |
|---|---|---|---|---|---|---|
| Talaud | Leang Sarru | 35 | Ono *et al.*, 2009; Kealy *et al.*, 2015 | 0.3 | 93.3 | 1654 |
| Moroti | Daeo 2 | 17 | Bellwood *et al.*, 1998; Kealy *et al.*, 2015 | 2 | N/A | 39 423 |
| Gebe | Golo Cave | 36 | Bellwood *et al.* 1998; Kealy *et al.*, 2015 | 3 | N/A | 644 |
| Sulawesi | Leang Timpuseng | 42 | Aubert *et al.*, 2014 | 59 | 70 | 227 360 |
| Alor | Tron Bon Lei | 21 | Samper Carro *et al.*, 2016 | 2 | 155.5 | 3862 |
| Kisar | Here Sorot Entapa | 15 | WK 43324 | 0.5 | 107.5 | 117 |
| Timor | Jerimalai | 43 | O'Connor *et al.*, 2014; Kealy *et al.*, 2015 | 3 | 128.5 | 31 583 |
| Roti | Lua Meko | 27 | Mahirta, 2003; Kealy *et al.*, 2015 | 7 | N/A | 2869 |
| — | — | — | — | — | — | — |
| Spearman's rho | | — | — | 0.56631 | –0.2 | 0.35714 |
| Probability | | — | — | 0.1504 | 0.68333 | 0.38938 |

Note: Measurements for site distance to the coast (in kilometres), site elevation (in kilometres) and island (island group) size (in $km^2$) interpreted from the palaeogeographic reconstructions at the maximum occupation date associated with each island. Spearman's rho for each set of variables is included. N/A, data not available.

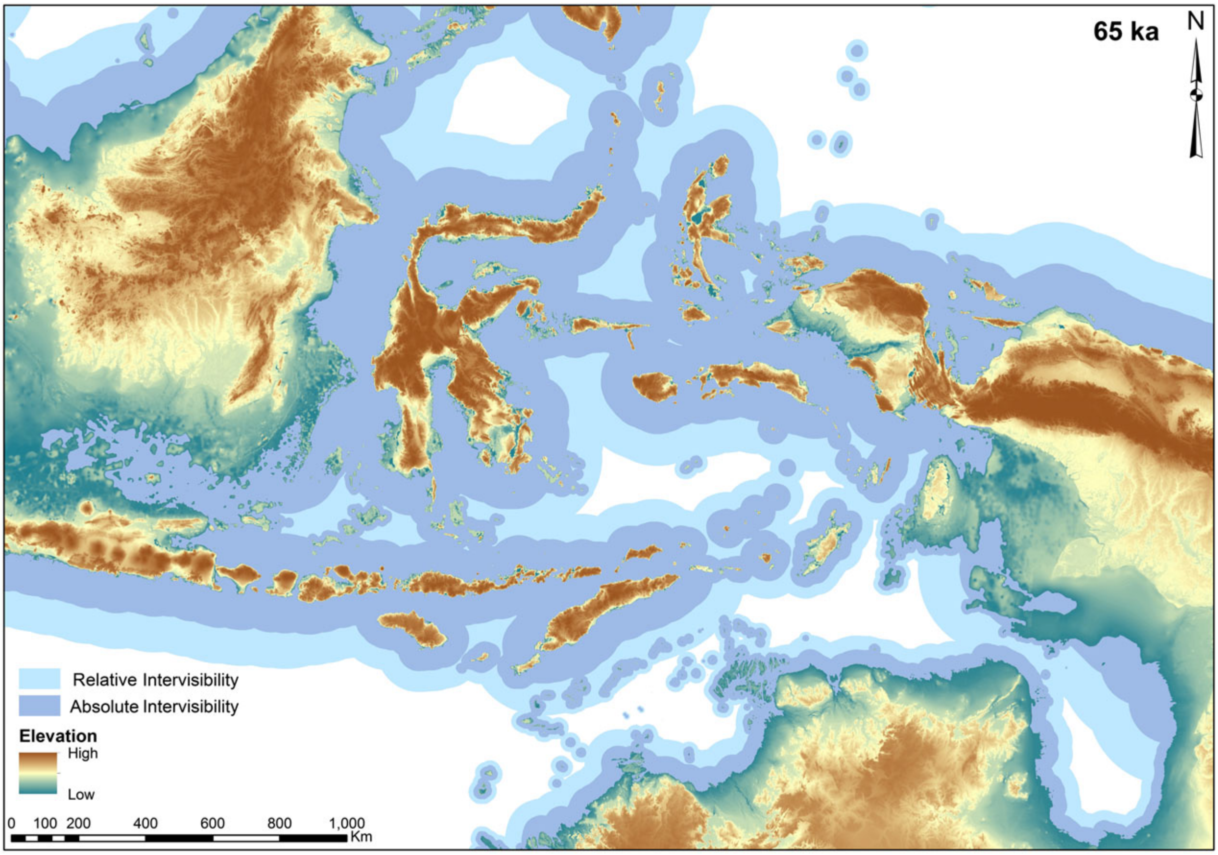


Figure 3. Palaeogeography reconstruction of the Wallacea Archipelago 65 ka ago, showing reconstructed topography and visibility buffers. The light blue buffer indicates regions of relative intervisibility, while the dark blue shows the estimated absolute intervisibility. [Colour figure can be viewed at wileyonlinelibrary.com]

would land have been visible from the south coast of Timor. Conversely, not only did northern Wallacea have continued relative intervisibility between Sunda and Sahul, but absolute intervisibility was also likely present between each 'stepping-stone' island along the way. While the visibility buffers may appear large,

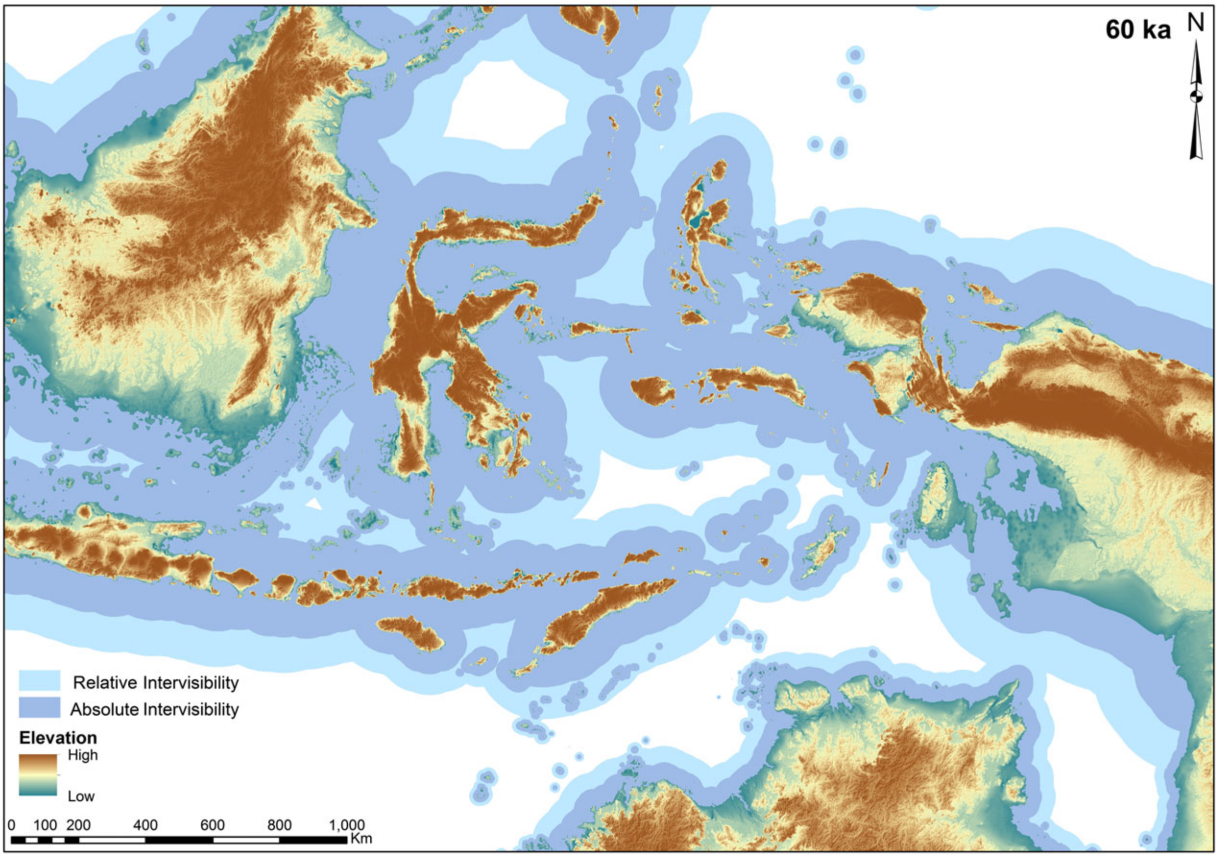


Figure 4. Palaeogeography reconstruction of the Wallacea Archipelago 60 ka ago, showing reconstructed topography and visibility buffers. The light blue buffer indicates regions of relative intervisibility, while the dark blue shows the estimated absolute intervisibility. [Colour figure can be viewed at wileyonlinelibrary.com]

we note that much of present day Indonesia already experiences significant relative intervisibility, and lowered sea-levels (and thus increased island heights) in the Pleistocene, as well as the emergence of small islands throughout the archipelago, adds significantly to the extent of the buffers.

Using the distance from the coast and elevation of the archaeological sites at their oldest known occupation, as well as the size of the island at that time (Table 2), we found no correlation between any of our geographic measurements and the dates of apparent initial occupation.

## Discussion

Birdsell's (1977) intervisibility study favoured two routes into Sahul (Figure 1). The first (Route 1B) ran from present day Borneo/Kalimantan, through Sulawesi and the Peleng islands, down to Ambon and Seram and up across to Misool. The second (Route 2B) route passed through Java and Bali, across to Lombok and through the Nusa Tenggara island chain into Timor and down onto the Fantone Bank on the exposed shelf of northwest Australia (Birdsell, 1977; Figure 1). The intervisibility models constructed here show the greatest support for a northern colonization of Sahul. Birdsell's Route 1B in particular is well supported by both relative intervisibility and the approximated absolute intervisibility. In addition to a landing point on Misool, our models also suggest the possibility of a landing site somewhere along the coast of the West Papua Fakfak Regency. Not only is intervisibility continuous between Seram and the Fakfak coast, but this part of Papua shows a high elevation that would have made it easy to spot by early colonizers. Future archaeological surveys both along the Fakfak coast and in Seram could provide the necessary data to test this hypothesis. For the route through Halmahera and onto the Papua Birds Head (Route 1A; Birdsell, 1977), relative intervisibility is continuous; however our estimate for absolute intervisibility is less connected than for the route through Seram.

The archaeological record, however, is less supportive of the northern route, with both the Wallacean and nearby Sahul (New Guinea) dates of occupation

 
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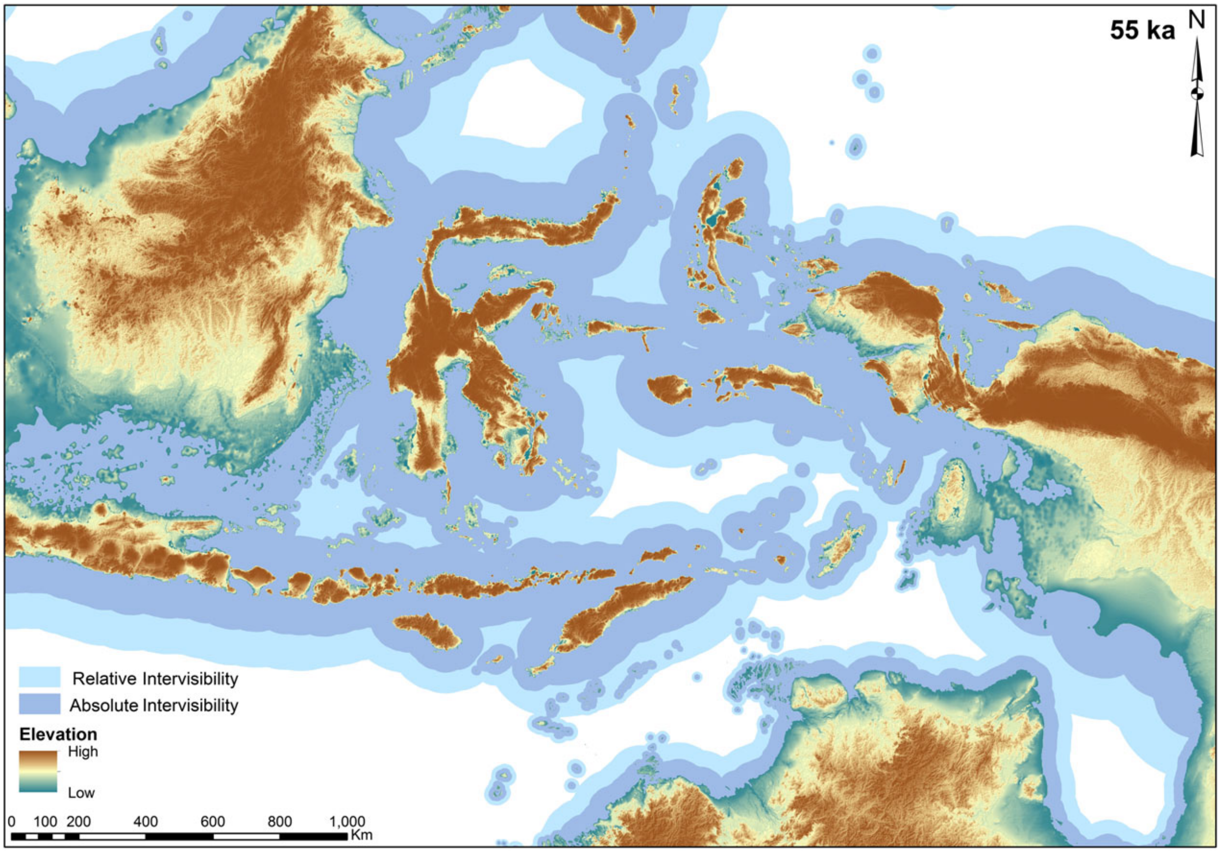


Figure 5. Palaeogeography reconstruction of the Wallacea Archipelago 55 ka ago, showing reconstructed topography and visibility buffers. The light blue buffer indicates regions of relative intervisibility, while the dark blue shows the estimated absolute intervisibility. [Colour figure can be viewed at wileyonlinelibrary.com]

lacking the antiquity of their southern route counterparts. A possible exception is the Vilakuav dates from the Ivane Valley in the highlands of Eastern New Guinea (Summerhayes *et al.*, 2010). While the oldest date recovered from this site has a range extending back to ca. 49 ka, it also has a minimum age of ca. 43 ka, making any further interpretations of the site in relation to the initial colonization of Sahul dependant on refinement of this date. Should the maximum date prove to be correct, the site's location in Eastern New Guinea (Figure 1) still leaves a large geographic and temporal dearth of archaeological sites along this route.

For the southern route, only the 65 and 45 ka reconstructions support Birdsell's (1977) Route 2B, however, they do suggest the same Fantone Bank landing location. The 65 ka reconstruction also shows relative intervisibility to the west, south of Roti through the present day Ashmore reef, to a landing point in the north Kimberly region. This south-western route currently receives little support from Wallacean archaeology (e.g. Mahirta, 2003), and the oldest dates from the Kimberly region (i.e. Carpenters Gap 1 and Riwi; Figure 1) do not extend back to 65 ka (Balme, 2000; Hiscock *et al.*, 2016; Wood *et al.*, 2016). Archaeological TL/OSL (thermoluminescence/optically stimulated luminescence) dates from Madjebebe do have ranges that overlap with the 65–62 ka period of intervisibility; however they suffer from large error margins that make further interpretations unreliable (Roberts *et al.*, 1990; Clarkson *et al.*, 2015). While Madjebebe's location in the central-north of Australia might suggest greatest support for a Fantone Bank landing site, with a lack of corresponding archaeological evidence, the possibility that the initial occupants did not arrive via the Kimberly or the northern routes through New Guinea cannot be ruled out. With the exception of the TL/OSL dates from Madjebebe (Roberts *et al.*, 1990; Clarkson *et al.*, 2015) the 65 ka reconstruction, whilst showing the furthest extent of southern intervisibility for our models and thus theoretically a better time for southern colonization, is also at the upper limit of models supported by archaeological and molecular data (Hill *et al.*, 2007; Hudjashov *et al.*, 2007; Oppenheimer, 2012; van Holst Pellekaan, 2013; Allen and O'Connell, 2014; Bergström *et al.*, 2016).



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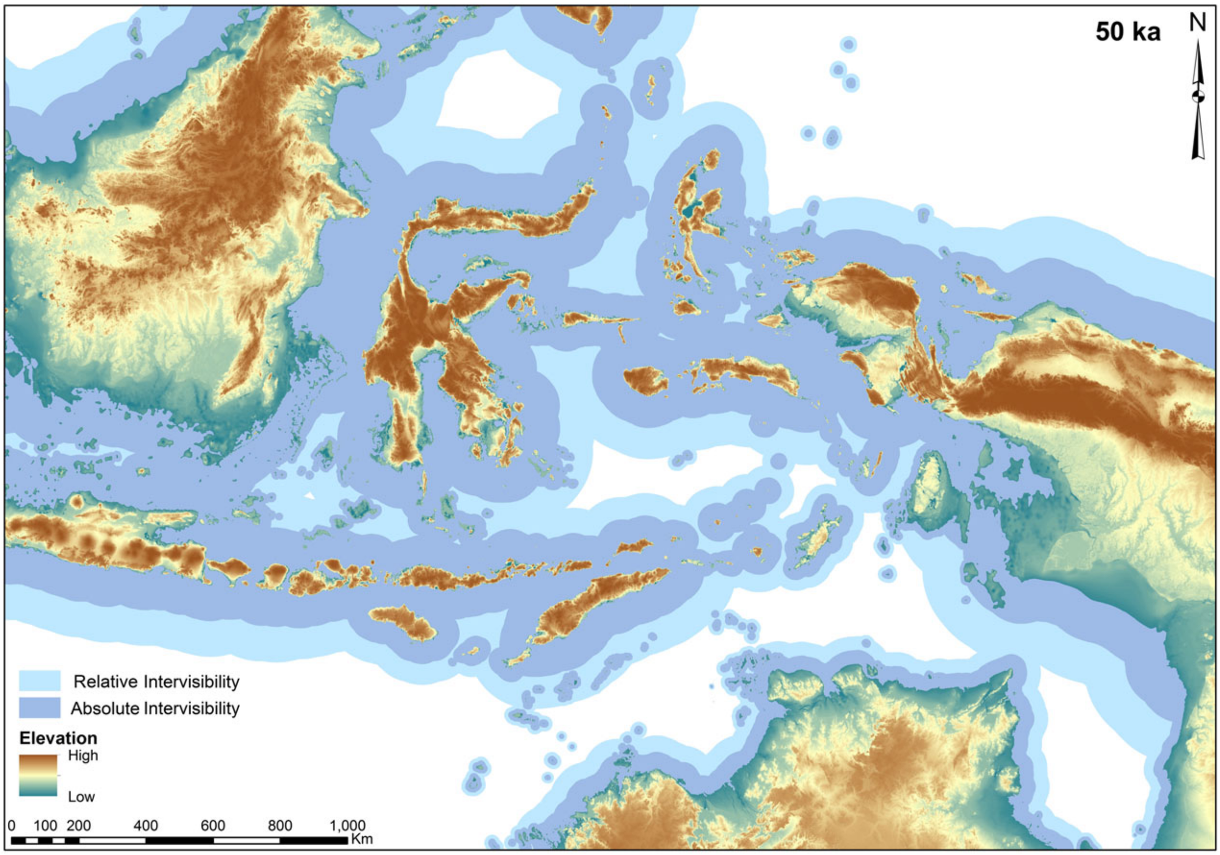


Figure 6. Palaeogeography reconstruction of the Wallacea Archipelago 50 ka ago, showing reconstructed topography and visibility buffers. The light blue buffer indicates regions of relative intervisibility, while the dark blue shows the estimated absolute intervisibility. [Colour figure can be viewed at wileyonlinelibrary.com]

Conversely, radiocarbon dates from Australia and Timor-Leste do overlap, with the latter dating within the range 47–12 ka when the south-eastern route between Timor and Sahul would have experienced continuous relative intervisibility (O'Connor, 2007; O'Connor *et al.*, 2010; Clarkson *et al.*, 2015; Hiscock *et al.*, 2016). Most archaeological and molecular studies, however, suggest an initial Sahul colonization event before 47 ka (Hudjashov *et al.*, 2007; Summerhayes *et al.*, 2010; van Holst Pellekaan, 2013; Clarkson *et al.*, 2015; Bergström *et al.*, 2016; Hamm *et al.*, 2016; Hiscock *et al.*, 2016), which our intervisibility study suggests was more likely from the north. Nevertheless, later colonization events from Timor could have occurred once relative intervisibility was established, supporting a multiple-colonization hypothesis (Birdsell, 1977; Ingman and Gyllensten, 2003; Oppenheimer, 2009; McEvoy *et al.*, 2010; Rasmussen *et al.*, 2011; Balme, 2013; van Holst Pellekaan, 2013).

Birdsell's (1977) Route 2A, from Timor through the Tanimbars and east to Aru and Sahul receives much greater support from our models than Route 2B. This latter route has continuous relative intervisibility in all our reconstructions, although our estimate for absolute intervisibility was absent at all times between 65 and 45 ka. There are archaeology sites along this route, in Kisar and Aru, however none of these have dates that extend to the dates associated with AMH colonization (O'Connor *et al.*, 2005a, 2005b). As intervisibility would have remained continuous between Timor and Aru until at least 12 ka, the later occupation dates of Kisar and Aru could be associated with later migrations from Timor along this route. Interestingly, the molecular study by Hudjashov *et al.* (2007) suggests colonization of Australia along the southern route, with Aru and the Fantone Bank as their two landing points. One of the haplogroup lineages to travel the Aru route (Route 2A) has a mutational separation date that overlaps with the oldest dates from the Aru excavations (O'Connor *et al.*, 2005a; Hudjashov *et al.*, 2007).

The alternative hypothesis that Sahul was colonized between 65 and 62 ka from Timor either to the Kimberly coast or Fantone Bank cannot be refuted on the basis of our study, and is not entirely lacking in archaeological or molecular support (Ingman and



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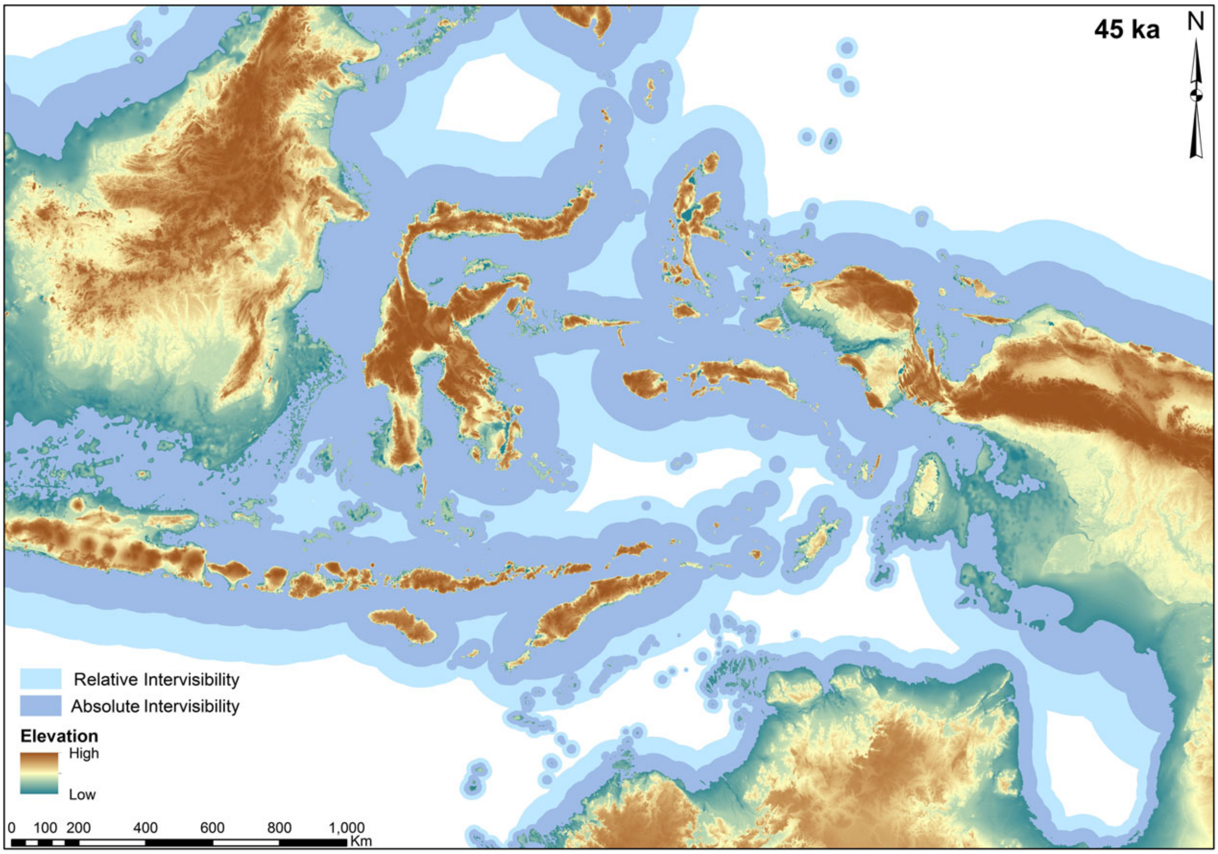


Figure 7. Palaeogeography reconstruction of the Wallacea Archipelago 45 ka ago, showing reconstructed topography and visibility buffers. The light blue buffer indicates regions of relative intervisibility, while the dark blue shows the estimated absolute intervisibility. [Colour figure can be viewed at wileyonlinelibrary.com]

Gyllensten, 2003; Oppenheimer, 2012; Clarkson *et al.*, 2015). As it is not supported by the majority of data available, however, we consider the possibility to be less likely than the later use of the northern route. Further archaeological investigations and dates from both Wallacea and Sahul will impact the likelihood of this scenario.

At a broader level, our reconstructions show a prehistoric island archipelago that was, visually, significantly inter-connected during the period of initial AMH colonization. Our models indicate that AMH exploration of the Wallacean Archipelago could have been far more extensive than previously suggested, as the vast majority of the Wallacean seascape was in sight of land between 65 and 45 ka. The dependency of early Wallacean communities on marine resources and their exploitation of both near-shore and off-shore environments (O'Connor *et al.*, 2002; O'Connor *et al.*, 2010, 2011; Samper Carro *et al.*, 2016) is consistent with these models, indicating that the vast majority of the Wallacean Archipelago's marine environments were accessible to AMH hunter-gatherers without the risk of travelling beyond sight of land. Such a situation is not only conducive to extensive and rapid island colonization, but also likely promotes the development of more specialized maritime technologies and a more maritime confident culture. The development of trade not only between neighbouring islands (e.g. Reepmeyer *et al.*, 2016) but also more extensively throughout the archipelago is rendered more likely considering the extent of relative intervisibility throughout the region. Intermittent occupation records, such as those of Leang Sarru in the Talauds (Ono *et al.*, 2009), might be explained by an archipelago with such extensive inter-island connections that a remote colony could easily move back to a larger island if conditions on the smaller island became less favourable. Similarly, initial landing by AMHs on the smaller islands of Wallacea may have occurred much earlier than their occupation records suggest, as their proximity to larger, colonized islands removes the necessity to occupy the islands permanently or semi-permanently, and reduces the risk associated with settlement of new and unfamiliar island environments.

In addition to the measures of relative and absolute intervisibility, other factors would have also



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contributed to AMH maritime knowledge as to the existence and direction of other islands. These indirect island indicators include different cloud formations, smoke from bushfires, cloud reflections, wind and current directions, phosphorescence, altered wave patterns, and the presence of birds in addition to migratory movements of birds and marine species (Keegan and Diamond, 1987; Irwin, 1989; Bednarik, 2001). Such indicators would have effectively increased an islands' measure of intervisibility, perhaps for some islands more than others, however the overall effect suggests a region of easy visual connectivity for its early human explorers. Of course, intervisibility and the knowledge of an islands' existence is not the only factor that would have influenced maritime explorations by AMHs. Other factors such as current and wind directions have long been recognized as significantly influencing the direction and likelihood of successful island colonization (e.g. Wild, 1986; Irwin, 1989). Our reconstructions provide a key aspect for any current or wind-based colonization model by indicating potential colonization sites identifiable by AMHs, while analyses of winds and currents help to understand the accessibility of these sites.

We used our palaeogeographic reconstructions to examine some basic geographical variables associated with the earliest occupation sites on different islands in Wallacea. That we found no correlation between initial occupation date and island size, distance to coast, and elevation is not surprising considering the low sample sizes currently available, and the fact that the earliest archaeological record on an island will post-date, sometimes quite significantly, actual earliest arrival. Furthermore, the processes controlling the discovery and preservation of archaeological deposits in tropical islands are complex, and relate to the interplay of factors beyond the geographic variables we examined, such as local geology, topography, hydrology, geochemistry, modern anthropogenic disturbance, and a certain level of serendipity (O'Connor *et al.* 2010, 2017; Morley, 2017). Whilst AMHs may have preferred coastal versus inland sites, or lowland versus upland areas when first arriving on islands, the data to test such hypotheses is not currently available, and given the many variables controlling site formation, discovery, and preservation, may never be.

Thus our palaeogeographic reconstructions provide no additional insights on where exactly to survey on any given island. However, they do provide indications of which islands should be targeted should one wish to test models of AMH movement towards Sahul. Specifically we suggest that, based on our reconstructions, archaeological surveys should focus on the northern route, in particular Seram, Buru, Taliabu and Peleng islands along Birdsell's Routes 1B/C. Based on intervisibility these islands appear to hold some of the greatest potential for future archaeological sites containing evidence of early AMHs. The islands along Birdsell's Route 2A such as Moa, Leti, Damar, Babar and the Tanimbar and Kai island groups also have potential for archaeological sites originating from either the initial Sahul colonization route or for a later migration. Archaeological exploration by the authors and colleagues, investigating some of these islands, is ongoing.

## Conclusions

Our palaeogeographic reconstructions indicate that the Wallacean Archipelago was visually more interconnected during the period of initial AMH colonization than previously thought. Furthermore, our study demonstrates likely relative intervisability between Timor and Australia during the range of possible colonization dates by AMHs, albeit at the extreme upper end of the colonization date range supported by archaeological data (Roberts *et al.*, 1990; O'Connor, 2007; Allen and O'Connell, 2014; Clarkson *et al.*, 2015). Relative intervisability for the period between 62 and 47 ka is notably absent.

On the basis of intervisibility alone, the northern route would have provided an easier migration for AMHs from Sunda to Sahul, and we suggest was the more likely route used for initial colonization. However, there is currently little in the way of archaeology to support this hypothesis. Our data also indicate that the northern route was not the only one possibly used by AMHs to reach Sahul, but that the southern routes through Timor to the Fantone Bank and Aru Island were possibly used later in the Pleistocene, following the emergence of greater intervisibility.

Future archaeological survey in the islands on the northern route such as Seram holds the potential to produce sites of significant antiquity. Our study also encourages future survey along the small island chain between Timor-Leste and Aru. Both areas hold potential for sites containing AMH deposits that pre-date the sites known from Australia. Should such antiquated sites be undetected, however, the intervisibility supports the hypothesis that they will still have sites of interest to our understanding of AMH movements through Wallacea during the later Pleistocene.

Our study supports the idea of a heavily maritime-based culture for the initial colonization period of Wallacea, facilitated by the major extent of



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intervisibility throughout the archipelago. The concept of such an inter-connected environment impacts the rates of colonization, likelihood of trade networks and occurrence of sporadic island use versus permanent colonization. Further discoveries on the small and remote islands of Wallacea hold the potential to provide the necessary data for testing these hypotheses.

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